BURGESS & NIPLE

Report

Professional Review of the Pinal Active Management Area's Groundwater Budget

Arizona Department Water Resources

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Since
1912

Pinal AMA Groundwater Budget Review – Final

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1.0 Introduction

Burgess & Niple (B&N) was retained by Arizona Department of Water Resources (ADWR) to conduct a review of the Pinal Active Management Area (AMA)'s groundwater budget. The Pinal AMA encompasses 4,000 square miles of South-Central Arizona. The area covered by the groundwater budget is approximately 1,800 square miles, including the Eloy and Maricopa–Stanfield subbasins (Figure 1). The groundwater budget period is from 1980 to 2002. The review evaluated the following primary groundwater inflow components:

- Groundwater underflow
- Agricultural irrigation recharge
- Urban irrigation recharge
- Canal recharge
- Artificial lake recharge
- Effluent recharge
- Artificial recharge
- Major drainage recharge
- Ungaged tributary inflow
- Basin and ephemeral stream recharge
- Mountain front recharge.

Outflow components include groundwater underflow, pumpage and evapotranspiration. The difference between the estimated total annual inflow and total annual outflow yields the annual change in storage.

B&N conducted an assessment of the methods and assumptions that ADWR used to derive each groundwater budget component. Various sources were utilized to research new methods for estimating some components. Based on the results of the review, this report provides for ADWR's consideration recommendations which we believe may assist in refining the groundwater budget to more accurately reflect field conditions.

2.0 Approach

B&N's objective was to evaluate the various water budget components in terms of general accuracy and overall applicability, with particular focus on those components of the budget that require estimation. To accomplish this, B&N conducted the review process in three steps. In the first step, B&N reviewed studies conducted within the Pinal AMA by various agencies (including ADWR, the U.S. Geological Survey (USGS) and the U. S. Bureau of Indian Affairs, etc.) to confirm the applicability and completeness of ADWR's choice of budget components. For instance, ungaged tributary stream inflow is not always incorporated into all water budgets. However, in this instance data is available for this component, and the inclusion of it provides a more accurate accounting of inflow.

In the second step, B&N reproduced ADWR's conceptual groundwater budget spreadsheet. The process took little time, but allowed the water budget calculations to be examined in detail for inconsistencies between the ADWR stated assumptions and methods, and those actually applied in calculations. Small calculation errors can also be detected during this exercise.

In the third step, the methods and assumptions used by ADWR for derivation of each water budget component were reviewed and evaluated in detail. Extensive research was conducted via publication research and personal communications with peers in the field of hydrology to validate some of the methods and assumptions, and to investigate for new, reliable, and well-accepted methods for groundwater budget analysis. Based on this research, recommendations that may aid in obtaining a more accurate and reliable groundwater budget for the Pinal AMA were provided for ADWR's consideration.

3.0 Review of Findings – Inflow Components

3.1 Groundwater Underflow

Groundwater underflow changes with groundwater flow field conditions, but it can be estimated through flow-net analysis and groundwater model simulations. ADWR's current estimates of groundwater underflow are based on several ADWR and USGS publications and the soon-to-be-published Tucson AMA model data. ADWR assumes that underflow estimates obtained from groundwater flow models that are calibrated with field data are expected to be most representative of underflow conditions, and that future hydrologic studies and modeling updates will help to further refine current estimates. B&N concurs with that assessment.

3.2 Groundwater Recharge Components

The Pinal AMA groundwater budget area consists primarily of the Maricopa-Stanfield and Eloy subbasins. Both subbasins are dominated by agricultural activities, which consume more than 96 percent of the total water used. Consequently, those components with greatest impact on the water budget are recharge from agricultural irrigation and canal seepage. Particular effort was spent on evaluating agricultural recharge and canal seepage due to their potential influences on the water budget.

Renewable water sources are those that enter the hydrologic system via an external source. Sources include precipitation within the study area and surface flows in tributaries. Groundwater pumped from and returned to the system is not considered to be a renewable source. Renewable sources that contribute to the water budget include major drainage, basin and ephemeral stream recharge, ungaged tributary stream inflow and mountain front recharge. Of these, major drainage recharge, which can be significant during wet years, has the greatest impact. The remaining renewable water sources have relatively little overall impact on the water budget. The mechanisms and processes associated with these renewable recharge components, however, are not fully understood at present. Estimation of these components often involves great uncertainty. For that reason, extensive research efforts were directed toward the investigation of new methods of estimating these inflow components.

3.2.1 Agriculture-Related Recharge

3.2.1.1 Agricultural Irrigation Recharge

Agricultural recharge represents water recharged to the regional aquifer as deep percolation from agricultural irrigation. It is estimated as the product of water applied to the land and the approximate irrigation inefficiency. With the advancement of irrigation technologies, irrigation inefficiency has been reduced over time. For the conceptual groundwater budget calculations, ADWR uses varying irrigation inefficiencies and assumes that agricultural recharge reaches the water table in the same year when water is applied to the land surface. The primary sources of water used for agricultural purposes include groundwater, Central Arizona Project (CAP) water, and diverted Gila River water. ADWR calculates agricultural recharge based on the total volume of water applied from each of the three sources.

Historical water use records indicate that the average annual agricultural water use for non-wet years is about 900,000 acre-feet per year (AFY). Agricultural water use during the wet years of 1983, 1992 and 1993 was about 600,000 and 700,000 AFY. B&N conducted an assessment of the potential impact of annual rainfall on agricultural water use. Based on the apparent difference between agricultural water use in wet years and non-wet years, B&N's initial interpretation was that precipitation in wet years substantially supplemented the water applied for agricultural irrigation from other sources. However, a review of the Arizona Agricultural Statistics annual report in 1982, 1983, and 1991 through 1993 indicates that the total number of acres harvested in Pinal County during those wet years was much less than in non-wet years. The reduction of agricultural acres was caused by economic factors, such as the government program of payment-in-kind (PIK) for crops not produced, and by natural factors, such as flooding in wet years that had prevented large areas from being cultivated.

Agricultural recharge lag time can be extensive in cropped areas where the depth to water is substantial, and where the existence of low permeability layers is extensive (Leighton & Phillips, 2003). ADWR previously applied agricultural recharge lag time to groundwater models developed for other AMAs. Don Pool, USGS, did not incorporate lag time in the groundwater model that he developed for the Eloy subbasin. However, during a recent telephone conversation with B&N, he concurred that lagged agricultural recharge should be applicable to the Eloy subbasin, though actual lag time can not be easily estimated. ADWR's current groundwater budget was developed as a "paper" water, or conceptual, budget. However, ADWR recognizes that agricultural recharge lag time is a potentially significant factor that should be accounted for in Pinal AMA's groundwater modeling simulations. ADWR intends to incorporate delayed agricultural recharge as the groundwater flow model for Pinal AMA is developed. For this review, B&N investigated the extent that agricultural recharge lag time may be applicable to the Pinal AMA.

Hydrographs for representative wells located in both Eloy and Maricopa-Stanfield subbasins were constructed using water level measurement data retrieved from the ADWR Groundwater Site Inventory (GWSI) database. Representative wells with relatively long-term and continuous water level measurement data were selected from both subbasins. Figure 2 and Figure 3 depict typical hydrographs for the Eloy and Maricopa-Stanfield subbasins, respectively. At the beginning of the water budget period, i.e., 1980, some wells in the Maricopa-Stanfield basin had water levels ranging from 500 to 700 feet deep. However, most of the wells within the two subbasins exhibited water levels ranging from approximately 200 feet to 300 feet deep. For subsequent analyses, the average depth to water for the study area is conservatively estimated to be 250 feet.

In addition to the large depth to water observed in this area, the distribution of aquitards appears to be extensive. According to Pool, et.al., (2001), the sediments of the Eloy and Maricopa-Stanfield subbasins are divided into lower, middle, and upper stratigraphic units. The principle aquifers in these subbasins are the conglomerate of the lower unit and the sand and gravel interbeds within the alluvial facies of the middle and upper units. The principal confining units (aquitards) are the playa facies of the lower, middle, and upper units, and the silt and clay interbeds within the alluvial facies of the middle and upper units. The existence of these low permeability layers in the upper and middle units contributes to the delay of agricultural recharge.

Agricultural recharge lag time is generally estimated using the average depth to water and the vertical water flow velocity, which is a function of many variables. The infiltration rate in the unsaturated zone is an on-going research topic for many vadose zone researchers. The USGS groundwater flow and land subsidence study (Leighton & Phillips, 2003) conducted for Antelope Valley, California, applied an agricultural recharge lag time based on the average depth to water and an average infiltration rate derived from a simple unsaturated zone study conducted on a silt loam. In that study, it was estimated that a lag time of 10 years would be required for water applied on the land surface to recharge an aquifer that has an average water level depth of 120 feet.

The vadose zone in the Pinal AMA study area is composed of sand and gravel interbeded with fine-grained materials such as silt and clay. During percolation, when water flows downward toward the water table, it is the low permeability layers that often limit the percolation rate. For purposes of this review, it is assumed that the percolation rate of 12 feet per year for silt loam may be applicable here. Using the assumed percolation rate and the conservatively estimated average depth to water of 250 feet, a lag time of 15 to 20 years may be reasonable for the Pinal AMA.

Estimates for lag time are supported by comparing the plotted historical pumpage with representative hydrographs in the study area. As exhibited on the two hydrograph figures, a majority of the wells show similar trends. Specifically, water levels decline continuously from the 1940's to approximately the early 1970's, then stabilize through the mid 1980's. Water levels begin to recover after the mid 1980's. Figure 4 shows the historical pumpage trend in the Pinal AMA. As illustrated on this figure, groundwater pumpage increased significantly from the 1940's to the 1950's, fluctuated and then declined slightly during the 1950's to the mid 1980's, and then decreased significantly from the mid 1980's to present, due to both increasing use of CAP water for irrigation and reduced farm activities. Well hydrographs for the area, however, do not reflect this activity. Delayed agricultural recharge could have caused the observed pattern, or it may be caused by other factors, including typical aquifer response due to pumping or delayed aquifer response due to aquifer compaction.

Generally, when an overdraft situation continues over a long period of time, the cone of groundwater depletion expands significantly. While a greater area of aquifer is impacted, water levels at the center of the cone continue to decline at a reduced rate and even stabilize. This phenomenon may be responsible, to a degree, for the apparent stabilization of water levels in the 1980's. The effect of delayed aquifer response due to aquifer compaction may also contribute to the apparent stabilization or recovery of water levels, and will be discussed in detail in Section 6.3, Impact of Land Subsidence. B&N believes that delayed agricultural recharge is a significant factor in apparent water level recovery at wells. It is suggested that under a recharge lag time of 15 to 20 years, the large quantities of agricultural water applied since the 1950's, with additional influence by the other two factors, contributed to the stabilization of water levels that were observed during the 1970's to 1980's.

It should be noted that actual lag time is difficult to estimate since it depends on site-specific conditions. The lag time may vary from one location to another and may not remain constant over the entire budget period. The lag time approximated in this report is a rough estimate, and this estimate can be better justified through groundwater flow model calibration. In addition, tracking concentration changes in certain groundwater constituents such as total dissolved solids through groundwater quality sampling, if they are available, may help to refine the estimate for lag time.

Applying agricultural recharge lag time impacts the agricultural recharge component of the Pinal AMA groundwater budget during the budget period. Compared to the years 1980 to 2002, a larger volume of water was applied for agricultural irrigation use from 1960 to 1982, while irrigation efficiency was much lower. The application of a recharge lag time of 20 years results in an estimated average annual agricultural recharge increase of nearly 102,000 AFY for the water budget period. This significant quantity of “missing” water may account for some of the discrepancy exhibited between the ADWR estimated conceptual groundwater budget and the observed water level trends in the Pinal AMA. It is important to recognize that applying a lag time does not create additional groundwater or add new water to storage. Instead, consideration of lag time simply accounts for the delay of previously recharged water to the water table by adjusting the timetable for some budget components.

3.2.1.2 Canal Seepage

Canal seepage represents the estimated amount of water that seeps from canals and laterals, and eventually percolates to the water table. Canal seepage in the Pinal AMA includes seepage through the CAP main aqueduct and laterals and the San Carlos Irrigation Project (SCIP) main canal and laterals. ADWR includes the Picacho Reservoir losses with canal seepage for calculation purposes. For purposes of this review, B&N is addressing the seepage from the Picacho Reservoir as the artificial lake recharge.

Seepage from CAP Canals

Canal loss rate is a function of many variables, including the physical dimensions of the canal, the lining conditions of the canal, numbers of wet and dry cycles, aquatic growth, sedimentation, and other factors. When canal loss study results are not available, the loss rate from canals must be estimated using alternative methods.

Canal loss studies have been conducted for CAP main aqueducts. According to a Central Arizona Water Conservation District (CAWCD) study conducted in 1989, the canal loss rate for the concrete lined CAP main aqueduct is about 0.062 ft/day. According to Jay Swihart, USBR, This rate compares favorably with the typical loss rate of 0.07 ft/day for canals with concrete liner and good joint filler. The total canal loss rate is derived from losses to evaporation and to canal seepage. The average seepage rate of the CAP main aqueduct is 0.015 ft/day (approximately 24 percent of the total loss rate), with a range of 0.01 to 0.02 ft/day. These numbers, provided by Patrick Dent, CAP, are based on yearly canal loss studies that have been completed since the CAP was in operation.

No canal loss studies have been conducted for CAP laterals. Unlike in the CAP main aqueduct, where water level is kept relatively constant by canal operators using check structures, the water level in laterals varies significantly due to varying volume of water delivered. As a result, these laterals may go through more frequent wet-dry cycles. The wetted perimeter, which is one controlling factor in estimating lateral seepage, changes frequently, making the estimation of seepage from laterals more difficult.

B&N believes that canal seepage can be most accurately estimated using seepage rate, canal length and wetted perimeters, when supportive data is available. However, with limited data available, ADWR's approach is a good alternative. ADWR used a conservative method for estimating seepage from CAP laterals. ADWR assumed that approximately 2.5 percent of the total water delivered is system loss, with 20 percent of that system loss being attributed to canal seepage and the remainder to evaporation/evapotranspiration. Unlined canals can show 30 to 50 percent canal losses. However, canal losses can be reduced by 95 percent if canals are lined and if canal joints are sealed (Jay Swihart, USBR). This has the effect of reducing the total canal loss to 1.5 to 2.5 percent. Therefore, the 2.5 percent system loss estimated by ADWR is a reasonable value to apply as system losses to the lined CAP canals.

Seepage from SCIP Canals

ADWR calculates seepage from SCIP project canals to include seepage from main canals, laterals and seepage from the Picacho Reservoir. Assumptions and methods regarding the Picacho Reservoir will be addressed in Section 3.2.3.1, Artificial Lake Recharge. Canal seepage depends primarily on whether or not the canal is lined. SCIP canals are not lined, therefore, canal seepage from these unlined canals yield the majority of the canal seepage in the Pinal AMA.

The method used by ADWR to calculate seepage from the SCIP canal is based largely on the nature of the data provided by SCIP. Main SCIP canal loss is reported in the SCIP annual report. Of the total main canal loss, 78 percent is reported to occur within the Pinal AMA.

Canal seepage from SCIP laterals is estimated as 75 percent of the difference between the water delivered to the agency/district and the water delivered to the land. The remaining 25 percent is assumed to be applied on farmlands as unaccounted for water. This percentage is derived based on local knowledge, and no supporting data has been provided. The reported losses are attributed entirely to lateral canal seepages, and no loss to evaporation is considered. The SCIP losses computed in this manner fall within acceptable ranges derived from calculated losses from unlined canals.

3.2.2 Natural Feature Recharge

The study area is a semiarid region with precipitation averaging about 8.5 inches annually. Major drainage recharge, ungaged tributary stream inflow, basin and ephemeral stream recharge, and mountain front recharge are generally limited, except in wet years, when recharge may become significant.

3.2.2.1 Major Drainage Recharge

Recharge due to infiltration of surface water flows in the Gila and Santa Cruz Rivers provides the major drainage recharge component of the groundwater budget in the Pinal AMA. Annual groundwater recharge from a river is generally estimated from an accounting of all stream flow accretions and losses.

Gila River

For the Gila River, ADWR assumes that there are no diversions and accretions between the Ashurst-Hayden Dam and the USGS gage near Laveen (#09479500), a stream reach of about 72 miles. ADWR also assumes that the difference between the Ashurst-Hayden Dam release data and the USGS stream gage data yields the maximum potential recharge. The stream infiltration rate per mile is considered to be constant over the entire reach. The maximum potential recharge, then, is prorated to the number of miles of Gila River inside the AMA (approximately 51.5 miles) to represent surface water that infiltrated to the regional aquifer for that portion of the Gila River within the AMA.

The method described above has been generally used to estimate stream recharge. A USGS study (Konieczki & Anderson) conducted in 1990 evaluated groundwater recharge along the Gila River as a result of the October 1983 flood. In that study, the 71 miles of Gila River stream reach between the Ashurst-Hayden Dam and the confluence of the Salt River is divided into four subareas. Subarea 1 includes the area from river mile 0 at the Ashurst-Hayden Dam to river mile 15. Subarea 2 extends from river mile 15 to river mile 22; Subarea 3 extends from river mile of 22 to river mile 40; and Subarea 4 extends from river mile 40 to the confluence of the Salt River. The study analyzed water level changes corresponding to the 1983 October flood for the 4 subareas along the Gila River. Results of the study indicate that water levels increased by about 26 feet, 59 feet, 21 feet, and 14 feet for Subareas 1 through 4, respectively. Greater water level increases were observed in the aquifer beneath the upper reaches of the river, indicating greater infiltration rates in the upper reaches. With this available information, it may be applicable to assign higher infiltration rates and therefore greater stream recharge to the upper 51.5 miles of Gila River within the Pinal AMA.

ADWR is currently investigating the use of a decay curve method to refine its original estimate of Gila River infiltration and to develop a more appropriate distribution of this recharge for the upper reaches within the Pinal AMA.

Santa Cruz River

The surface water flow in the Santa Cruz River has two components: the natural flow that results from precipitation events, and the effluent released into the Santa Cruz riverbed. The effluent discharged to the Santa Cruz riverbed includes effluent released from the Casa Grande wastewater treatment facility and effluent released from the Ina and the Rogers Road wastewater treatment facility. In ADWR's budget, the effluent released from Casa Grande wastewater treatment facility is not included in the Santa Cruz flows, but is listed separately as an effluent recharge in the AMA. The effluent component of the Santa Cruz River recharge in the budget refers solely to the effluent released from the Tucson area.

According to ADWR-provided data, after 1989 the Santa Cruz River infiltration recharge, including both natural and effluent components, were estimated based on records of the Trico Road gage located approximately 5.5 miles upstream from the Pinal-Tucson AMA boundary. From 1980 to 1989, overall flows into the Pinal AMA were estimated based on gages located further upstream than the current Trico Road gage. Surface water flows from effluent released into the Santa Cruz riverbed for this period were not specifically estimated at present due to the lack of a surface water gage close to the Pinal AMA -Tucson AMA boundary. B&N identified the missing effluent component for this period on ADWR's water budget when B&N found that Santa Cruz River recharge was estimated to be zero for five of the years between 1980 and 1989 (1980, 1982, 1986, 1987, and 1988). ADWR is aware of this missing component and will develop other methods to estimate the amount of potential surface water flows into the Pinal AMA as a result of effluent released from Tucson area from 1980 to 1989.

3.2.2.2 Ungaged Tributary Inflow

Ungaged tributary stream inflow represents surface water flows in ephemeral washes that originate outside of the Pinal AMA but enter the AMA and become a potential source of infiltration to the regional aquifer in the Pinal AMA. Los Robles, Brady, and McClellan washes have large drainage areas and the potential to discharge large and periodic flood flows into the Pinal AMA.

Regression equations are often used by various researchers in an attempt to estimate runoff of ungaged ephemeral streams. Some regression equations primarily use channel geometry data, while many other equations correlate runoff to the physical attributes of the drainage basin. Nevertheless, almost all methods involve uncertainties.

ADWR has followed the research of Osborn et.al., 1971; Hedman and Osterkamp, 1982; Moosburner, 1970; and Stiehr, 1981 to obtain four equations for estimating ungaged tributary inflow. Before their applications to the Los Robles, Brady, and McClellan Wash, these four methods were evaluated by ADWR in terms of their accuracy using available gaged stream data on the upper reaches of Los Robles, the Altar Wash and the Brawley Wash. Evaluation results showed that estimation errors ranged from 21 percent to 340 percent.

Being aware of the potential significant errors associated with each method, ADWR chose to be conservative regarding the estimated tributary inflow for the three washes, and the averaged lower value of the estimated runoff for each method was chosen to represent the inflow value. B&N believes that ADWR has taken the right approach to derive this recharge component.

Additional simple evaluations of the estimated ungaged tributary inflow can be conducted to validate ADWR's approach. With the knowledge of the drainage areas of Altar Wash and Brawley Wash and their measured runoff, as well as the drainage areas of Los Robles, Brady, and McClellan Washes, the average annual stream flow in the three washes can be estimated based on the ratios of drainage areas. The estimated inflow can then be compared with ADWR's original estimate to see if the two estimates are in good agreement.

3.2.2.3 Mountain Front Recharge

Mountain front recharge represents water that infiltrates down to the local water table through washes in the mountains as sheet flow or stream infiltration on alluvial fans at the foot of mountains. This water flows down out of the mountains and alluvial fans into the regional aquifer. Following the study by Anderson (1986) and Watson, et.al.,(1976), ADWR demonstrated that little recharge occurs in the southwestern alluvial basins if precipitation is below eight inches per year. However, precipitation usually increases with elevation, so it is likely that higher elevations can receive sufficient rainfall to generate some recharge.

Mountain precipitation in central Arizona is usually greater than 8 inches but not likely to exceed 15.5 inches. Since only low-relief mountains exist within the study area, the volume of mountain front recharge as a percentage of the known precipitation is expected to be limited. The highest elevations in the AMA are the Picacho Mountains and Table Top Mountain. They are both between 4,000 and 4,500 feet in elevation. Table Top Mountain is much smaller in general size and is believed to contribute much less recharge.

For the Pinal AMA groundwater budget, ADWR used the upper end of the range of estimated values as provided by researchers for mountain front recharge, or 1,000 AFY. In the ADWR's Report No. 1, 1989 (Corkhill & Wickham), a different method is used to calculate mountain front recharge by applying a percentage of precipitation ranges to the total contributing area for the Picacho Mountains from Picacho Peak to South Cactus Forest, estimated to be 6,429 acres. This method estimated mountain front recharge to range from 129 AFY to 526 AFY, with an average of 327 AFY.

Anderson, et.al., (1992) conducted a study on alluvial basins in south-central Arizona, where a regression equation was established between the average mountain-front recharge (Q rech) and the total annual volume of precipitation on the watershed when the precipitation (p) is in excess of 8 inch/year.

$$\text{Log Q rech} = -1.40 + 0.98 \log P, \text{ where } P>8 \qquad (1)$$

Substituting the highest precipitation rate of 15.5 inches, and the ADWR-estimated total contributing area of 6,429 acres into the above regression equation yields an estimate of the maximum average mountain front recharge of 276 AFY. This value compares favorably with ADWR's previous estimate, but indicates that the value used in ADWR's groundwater budget is likely overestimated. B&N estimates that mountain front recharge in the Pinal AMA should be no more than 500 AFY.

3.2.2.4 Basin and Ephemeral Stream Recharge

Basin and ephemeral stream recharge represents water that recharges the regional aquifer from occasional, short-term flows that occur in washes as a result of summer thunderstorms or long-term winter storms.

The primary methods employed to estimate ephemeral channel recharge include water balance, chloride concentration change, natural tracers, and microgravity measurements of water mass change (Goodrich, et.al., 2004). All of these methods require extensive fieldwork to develop a good estimate.

Without extensive fieldwork, ephemeral stream recharge can be estimated as a certain percentage of the precipitation. In arid and semi-arid regions there is mounting evidence that recharge is likely to occur in only small portions of a basin, where flow is concentrated, such as depressions and ephemeral stream channels (Goodrich, et.al., 2004). Based on extensive literature review, ADWR assumed that basin wide ephemeral stream recharge in the Pinal AMA can be approximated to be 1% of total long-term precipitation falling on the basin/watershed with the recharge mainly transmitted through ephemeral washes. B&N concurs that the 1% of long-term precipitation is a reasonable estimate. The average annual precipitation on the valley floor of the Pinal AMA is about 8.4 inches. Basin area is assumed to be 1,156 square miles or 740,000 acres. The long-term ephemeral stream recharge is then estimated to be 5,000 AFY.

ADWR intends to monitor research regarding ephemeral stream recharge in arid and semi-arid basins, and may modify its current estimates based on future studies and findings.

3.2.3 Non-Agricultural Recharge

3.2.3.1 Artificial Lake Recharge

Picacho Reservoir has primarily been used as an irrigation water storage facility. To calculate seepage from the Picacho Reservoir, ADWR first calculated the operating loss of the Picacho reservoir at 55% of the reservoir's inflow. This percentage is derived as a calculated average ratio of the reported annual water loss to annual inflow over a period of 13 years (1981 to 1993). The total operating loss of the reservoir is then separated into two elements: 62% to evapotranspiration and 38% to reservoir seepage. These percentages were developed by Pinal AMA for the period of 1981 to 1993, when total reservoir inflow was about 35,000 AFY.

Since 1993, inflows to the reservoir have significantly declined. For instance, the average inflow for the period of 1994 to 2000 was about 20,000 AFY, only 57 percent of the average inflow for the period of 1981 to 1993. The major consequence of the significantly reduced inflow is the die-off of the riparian vegetation. No field work was conducted during this period to estimate how the total loss is divided into ET loss and seepage loss.

B&N believes that seepage losses from the Picacho Reservoir may be underestimated. By averaging the elements of this component over many years and applying a percentage of the result as a constant, small differences are multiplied throughout the calculation process, adding uncertainty to the derived calculations. For example, during the period of 1980 to 1993, the average annual reported operation loss was 22,607 AFY. The average operation loss calculated using 55 percent of inflow is 19,455 AFY. The difference of 3,152 AFY represents missed annual water losses. This adds up to several thousand acre-feet over the time period. Since records of annual operating losses for the Picacho Reservoir are available, B&N recommends that original data be used instead of the calculated estimates based on the 55-percent relationship. ADWR intends to reevaluate seepage loss from the Picacho Reservoir using reported data.

Reservoir seepage is the only element applied to the artificial lake recharge component of the budget. The evapotranspiration element for Picacho Reservoir is not included in the groundwater budget as it represents losses of stored surface water instead of groundwater.

3.2.3.2 Effluent Recharge

According to the stated assumptions and methods for this component, ADWR interprets effluent recharge data provided by the Pinal AMA as representing recharge to the aquifer from effluent released into the Santa Cruz riverbed by the Casa Grande wastewater treatment plant. The reclaimed effluent generated by Casa Grande wastewater treatment facility is actually delivered to various users, including municipal golf courses, an electric power generating station, farmlands and discharged to the Santa Cruz riverbed.

Pinal AMA bases the volume of effluent recharge primarily on the estimated volume of effluent that is delivered to farmlands. According to Joe Singleton, Pinal AMA, effluent recharge is calculated as the product of the estimated amount of effluent applied to the farmland and irrigation inefficiency, at 95 percent percolation efficiency. Currently, there is no accounting system for the effluent generated, and no accurate data for deliveries is available to ADWR for inclusion in the groundwater budget. Pinal AMA provides to ADWR an estimated effluent recharge volume, which ranges from 1,230 AFY to 1,496 AFY.

Municipal and Industrial (M&I) water use, though increasing with time, is a relatively insignificant fraction of the total water use. As a result, effluent recharge of all types has little impact on the water budget, especially compared to the impact of agricultural recharges. Water use records indicate that the M&I water use in Pinal AMA increased continuously from 18,000 AFY in 1980 to 37,568 AFY in 2002. It is reasonable to assume that in Arizona, 37 to 40 percent of this total M&I water use may return as reclaimed water available for recharge, either through public treatment systems or private septic systems.

Currently, there is no requirement to report to ADWR the comprehensive information concerning effluent production and use. The accurate volume of effluent discharged to the Santa Cruz riverbed is not known. The volume that is currently estimated as effluent recharge is based only on that portion of effluent applied to farmlands and may be slightly underestimated. With the exception of treated effluent delivered to the power generating station, the remainder of the treated effluent should be available as recharge. Taking into account of efficiency quotas, approximately 37 percent of the treated effluent should be available for recharge to the aquifer through the various uses.

3.2.3.3 Urban irrigation recharge

According to ADWR, the urban irrigation recharge represents an estimated amount of incidental recharge resulting from flood irrigation water applied to urban areas such as parks, golf courses, or other turf areas. Pinal AMA estimated that 4 percent of the total municipal and industrial water use may attribute to urban irrigation recharge. This value is the same as that used in other AMA's for incidental recharge.

3.2.3.4 Artificial recharge

There are no large on-going artificial recharge projects in the Pinal AMA except for the limited amount of reclaimed effluent released from Florence wastewater treatment facility to the Santa Cruz riverbed. Artificial recharge represents the amount of reclaimed effluent released from the Florence wastewater treatment facility and recharged through a recharge project since 1989. Currently, this component is negligible, but may become more significant over time.

4.0 Review of Findings - Outflow Components

4.1 Groundwater underflow

Groundwater underflow can be estimated using flow-net analysis and groundwater model simulations. Groundwater underflow changes with groundwater flow field conditions. ADWR estimates groundwater underflow based on several ADWR and USGS publications and the soon-to-be-published ADWR Tucson AMA model data. B&N agrees with ADWR that underflow estimates obtained from groundwater flow models that are calibrated with field data are the most representative of underflow conditions.

4.2 Groundwater Pumpage

Groundwater pumpage in the Pinal AMA includes Indian agricultural pumpage and all pumpage reported through Registry of Groundwater Rights (ROGR) including non-Indian agricultural pumpage and M&I pumpage. Indian agricultural pumpage includes pumpage for Tohono O'Odham (Chui Chi), Ak-Chin, and Gila River Indian Community.

Groundwater pumpage shows a general declining trend over time. It varies from about 238,000 AFY to 998,000 AFY during the period 1980 to 2002. The lowest groundwater pumpage occurred in 1993 and the largest pumpage occurred 1981. According to Pinal AMA, the low groundwater pumpage occurred in 1992 and 1993 was primary due to economic factors. Specifically, in 1992, in order to relieve farmers/districts' financial burden initiated by the "Take or Pay" provisions of CAP water, CAWCD agreed to in-lieu use under the condition that farmers/districts reduced their groundwater pumpage. This in-lieu recharge program was discontinued in 1994.

B&N spent little effort on reviewing ADWR's groundwater pumpage data based on the assumption that pumpage data involves the least uncertainty among all the water budget components.

4.3 Evapotranspiration

Evapotranspiration (ET) represents the estimated amount of groundwater lost through transpiration from plants that utilize groundwater.

According to ADWR, a major area of groundwater-sustained riparian vegetation exists along the channels of the Gila and Santa Cruz rivers in the northern portions of the Maricopa-Stanfield basin on the Gila River Indian Community. This area is characterized by shallow groundwater conditions and dense growths of mesquite and salt cedar. Although this riparian area is physically located within the Pinal AMA, the area is outside of the Pinal AMA water budget area. Therefore, ET occurring in this area is rightfully excluded from the groundwater budget.

Evapotranspiration occurs along the Santa Cruz River in the Green's Wash area where effluent flows enter the Pinal AMA from the Tucson AMA, as well as downstream from the point of release for Casa Grande's wastewater treatment facility. ADWR considers this volume to be negligible with respect to the groundwater budget. B&N concurs with this assessment.

The only ET losses included in the ADWR groundwater budget analysis consist of the ET loss from the thin band of riparian vegetation that lines the Florence Casa Grande canal and the loss from both the open water surface of the Picacho Reservoir and the riparian vegetation that grows within the Picacho Reservoir. ADWR estimates the riparian acreage associated with the Florence canal is about 72 acres, and the estimated ET loss is about 300 AFY. B&N agrees that this ET component reduces canal seepage to the underlying aquifer, and that these riparian acres consume groundwater, although in an indirect way.

As shown on ADWR's groundwater budget, the largest ET component comes from the Picacho Reservoir. According to ADWR, the Picacho Reservoir covers an area of 2,508 acres. Historically, riparian growth covered about 1,984 acres of the reservoir area, and open water surface covered about 524 acres. The ET loss from the riparian vegetation growing in the reservoir and the evaporation from the open water surface of the reservoir is estimated at 62 percent of the operating loss of the Picacho Reservoir. Water in the Picacho Reservoir is actually diverted Gila River water, which is surface water. Therefore, the estimated ET is actually a loss of surface water stored in the reservoir instead of a loss of groundwater. ADWR concurrs that this ET component should be excluded from the groundwater budget.

5.0 Change in Storage

The annual aquifer change in storage equals the difference between the annual total inflow and total outflow. Based on evaluations of the groundwater budget derived by ADWR, B&N recommends that some inflow and outflow components should be re-estimated. These revised estimates of inflow and outflow components may yield a refined value for aquifer change in storage.

Some of the component refinements suggested by B&N require additional data collection and analyzing effort. In this report, B&N has provided only approximations of those recharge components in an effort to provide an indication of the impact on the change in storage. ADWR may choose to derive detailed and accurate estimations of these water budget components following B&N's recommendations. For some components, insufficient data was available to B&N to provide even general recommendations. All recommended inflow and outflow component value ranges provided by B&N are listed in Table 1.

5.1 Change in Inflow Components

To aid in this evaluation and review, B&N recreated ADWR's budget calculation spreadsheet. This allowed for a minute examination of the application of methods and accuracy checks. It also presented an opportunity to test the impact of B&N's proposed modifications. This section describes the inflow components modified by B&N for testing.

Of all the inflow components, underflow, urban irrigation recharge, artificial recharge, basin and ephemeral stream recharge, and ungaged tributary inflow are considered to be reasonably estimated, and no changes have been suggested.

The Picacho Reservoir recharge, which is calculated as part of the canal recharge by ADWR, has been incorporated into the B&N revision as artificial lake recharge. B&N reevaluated the Picacho Reservoir recharge using the actual reported water loss. The revised recharge values ranged from about 9,800 AFY in 1980 to about 750 AFY in 2002. B&N's estimate adds an annual average of more than 2,000 AFY to the groundwater budget.

To estimate effluent recharge, B&N assumes that 40 percent of M&I water use can become effluent, and that, conservatively, 37 percent of the reclaimed water can infiltrate the regional aquifer. This is based partly on agricultural irrigation inefficiencies and stream channel recharge credit. Following these assumptions, B&N estimates that annual effluent recharge can be estimated at about 3,300 AFY, more than twice the estimate provided to ADWR by Pinal AMA. This is an estimate only, and further investigation should be conducted to verify effluent deliveries.

For purposes of this exercise, it is assumed that the deep percolating agricultural recharge will take 20 years to reach the regional water table. Agricultural recharge is estimated using agricultural water use between 1960 and 1982, the agricultural irrigation inefficiency of 35 percent, and an additional 5 percent loss during percolation. As a result, the revised estimate for agricultural recharge ranges from approximately 266,000 AFY to 423,000 AFY during the water budget period of 1980 to 2002, with an average agricultural recharge of 345,000 AFY. This increases the apparent annual average agricultural recharge by nearly 102,000 AFY over current ADWR's estimate. It should be noted that B&N's estimate of lag time is simply a rough approximation and it can be better refined through Pinal AMA groundwater flow model calibrations supported with field data.

Major drainage recharge has two primary components, the Gila River infiltration recharge and the Santa Cruz River recharge. For the Gila River recharge, B&N suggests that ADWR investigate the applicability of higher infiltration rates in the upper reaches of the river. B&N understands that further research may be necessary to make valid predictions of these infiltration rates. ADWR is currently investigating the use of a decay curve method to refine its current estimate of the Gila River infiltration recharge. B&N did not modify ADWR's current estimation of this component.

Santa Cruz River infiltration has two components, the natural flow components and the effluent component that originates in the Tucson AMA. It is suspected that the effluent component from the Tucson AMA was omitted during the period from 1980 to 1988. ADWR calculated the average percentage of the total Tucson AMA effluent entering Pinal AMA for the 10-year period 1990 to 1999. B&N used this percentage to estimate the effluent component for the time period of 1980 to 1988, and applied these effluent estimates to Santa Cruz River infiltration recharge for the period of 1980 to 1988. As a result, river recharge during this period increased by slightly more than 2,500 AFY.

Not all inflow components were recommended to be revised to larger volumes. B&N believes that a reasonable estimate of mountain front recharge should be approximately 500 AFY.

5.2 Changes in Outflow Components

B&N believes that the underflow and pumpage outflow components are reasonably estimated. However, evapotranspiration may be overestimated. The groundwater budget evaluates groundwater inflow and losses, so this component must apply to groundwater lost through ET. Since the primary element of this outflow is loss of diverted Gila River water stored at the Picacho Reservoir, this component is not truly a groundwater loss. The average annual estimated ET is about 9,741 AFY. This component was omitted from the B&N calculation.

Table 1 Recommended Application for Inflow/Outflow Components

Inflow Components	*Component Application*[1]	*Modification Recommended*
Underflow	32,500 to 82,000[2]	
Agricultural Irrigation Recharge	Varies per formula and annual use	X
Urban Irrigation Recharge	Varies per formula and 4% M&I annual use	
Canal Recharge	30,000 to 130,000 AFY Varies with annual use	
Artificial Lake Recharge	500 to 15,000 AFY Varies with annual use	X
Effluent Recharge	2,700 to 6,000 AFY Varies per formula and M&I use	X
Artificial Recharge	0 to 250 AFY As reported	
Major Drainage Recharge	3,500 to 650,000 AFY Subject to rainfall events	X
Ungaged Tributary Recharge	750 to 5,250 AFY (based on averaged annual precipitation)	
Mountain Front Recharge	250 to 500 AFY	X
Basin / Ephemeral Stream Recharge	Insufficient data to recommend value range	
Outflow Components		
Underflow	6,560 to 17,040 AFY	
Pumpage	230,000 to 1,000,000 AFY	
Evapotranspiration	300	X

Notes:

[1] Values apply through 2002 groundwater budget

[2] Based on ADWR budget. This value may be modified upon review of the Tucson AMA groundwater model.

Table 2 Comparisons of Pinal AMA Renewable Water Budget

Water Budget Components	**ADWR**				**B&N**			
	Long Term Average	Range of Values			Long Term Average	Range of Values		
Inflows (AFY)								
Underflow	***57,350***	32,700	to	81,700	***57,350***	32,700	to	81,700
Major Drainage Recharge[1]	***28,200***	17,800	to	39,500	***28,200***	17,800	to	39,500
Ungaged Tributary Inflow	***3,000***	750	to	5,250	***3,000***	750	to	5,250
Mountain Front Recharge	***1,000***	1,000	to	1,000	***500***	500	to	500
Basin and Ephemeral Stream Recharge	***5,000***	5,000	to	5,000	***5,000***	5,000	to	5,000
TOTALS	**94,550**	57,250	to	132,450	**94,050**	56,750	to	131,950
Outflows (AFY)								
Underflow	***(11,800)***	(6,560)	to	(17,040)	***(11,800)***	(6,560)	to	(17,040)
Net Long-term Renewable Supplies (AFY)	**82,750**	50,690	to	115,410	**82,250**	50,190	to	114,910

Note: AFY = acre-feet per year; GRIC = Gila River Indian Community

1. Per the recommendation of this report, ADWR modified the method for estimating the Gila River recharge within the Pinal AMA, and provided the adjusted recharge estimate on November 22, 2004. Major drainage recharge has two components: the Gila River recharge and the Santa Cruz River recharge. For the Gila River recharge component, only recharge occurred along the Gila River stream reach of approximately 19.3 miles between the Ashurst-Hayden Dam and the Pinal AMA - GRIC boundary is included. The total estimate of the Gila River recharge is distributed non-linearly along the entire stream reach, and a greater percentage of river recharge is attributed to the upstream portion of the Gila River. For the Santa Cruz River recharge, the estimate does not include the effluent component released from Tucson AMA.

6.0 Explanation of Results

As B&N assessed the various components of the Pinal AMA groundwater budget, it became apparent that historical water levels measured in wells within the AMA could provide information to support modification of the groundwater budget through the introduction of agricultural recharge lag time. At the same time, it cannot be assumed that increased water levels directly equate to increased aquifer storage.

6.1 Water Level Recovery

There are two primary elements that likely contribute to the observed recovery of regional cones of depression within the Pinal AMA. The first element is the reduction in groundwater pumpage from historic high levels in the 1950s through the 1970s. Reduced pumpage significantly contributed to water level recovery. The second element is the impact of land subsidence on both water level increases and aquifer storage. Land subsidence may conceal reduced aquifer storage by exhibiting higher water levels.

ADWR will evaluate the potential impacts of these factors in future updates of the Pinal model. B&N believes that each of these elements contributes to the conditions observed in the study area, and aids in explaining the results obtained in B&N's evaluation. The impact on the groundwater budget associated with the agricultural recharge lag time and land subsidence is discussed below.

6.2 Change in Storage

B&N applied adjusted estimates of some annual inflow and outflow components to ADWR's conceptual budget spreadsheet. Many of the modifications actually had little effect on the current budget because of their proportionately small values. (Note: as conditions in the study area change, the impact of these components on the budget may increase.) The component with the greatest impact on the groundwater budget was the modification that incorporated lagged agricultural recharge.

The modified components were applied to the spreadsheet, producing a graph of the calculated aquifer change in storage. The graph indicates that the various inflow and outflow components had the cumulative effect of producing a positive change in aquifer storage. Figure 5 depicts the B&N-estimated annual change-in-storage and the accumulated aquifer storage over the 22-year water budget period. Note that the temporal trend of the change in aquifer storage closely matches the trend exhibited on the hydrographs for the Eloy and Maricopa-Stanfield subbasins. In other words, the water level trends closely reflect the apparent aquifer storage trends. The good agreement between these plotted data supports the conclusions made by B&N.

6.3 Impact of Land Subsidence

The substantive groundwater withdrawals that occurred between the 1940's and the mid 1980's in the Eloy and Maricopa-Stanfield subbasins resulted in significant aquifer compaction and severe land subsidence. According to Laney and others (1978), by 1977 approximately 655 square miles of land area had subsided in the Eloy subbasin, where the maximum subsidence was 12.5 feet. About 425 square miles of land area had subsided in the Maricopa-Stanfield subbasin, where the maximum subsidence was 11.8 feet.

With the onset of CAP water use beginning in 1987, and the subsequent reduction in groundwater withdrawals, water levels at most wells began to recover in the Eloy and Maricopa-Stanfield subbasins. A recent USGS study (Evan and Pool, 2000) showed that the effects of historic pumping on the aquifer are still evident as aquifer compaction and land subsidence continue, despite significant water level recoveries.

As noted earlier, the upper aquifer system in the Pinal AMA is made up of aquifers that are composed of sand and gravel deposits and thick aquitards of extensive playa deposits consisting of fine-grained deposits of silt, clay, or evaporates. Groundwater occurs in both aquifers and aquitards. During the several decades of aquifer overdraft, water levels declined significantly, creating vertical gradients between aquifers and aquitards. Vertical gradients drive the fluid-flow between these aquifers and aquitards. As water starts to be released from storage in the aquitard, fine-grained materials compact readily, and the overburden settles at an accelerated rate.

The thickness of the aquitard affects the rate and the duration of aquifer system compaction. Fluid pressure in aquitards of significant thickness equilibrates with the fluid pressure in surrounding coarse-grained material at a much slower rate than it occurs in thin aquitards. Hydraulic heads in aquifer material surrounding the thick aquitard may recover to levels higher than the preconsolidation head, but compaction may continue to occur until the hydraulic head within the thick aquitard equilibrates with hydraulic heads in the surrounding coarse-grained deposits. This equilibration can take years to complete and is termed residual compaction. In the Eloy and Maricopa-Stanfield subbasins, the aquitards are distributed continuously in space and are of great thickness. The existence of these thick aquitards resulted in long-term residual compaction as observed in measurable land subsidence. Residual aquifer compaction continued in the Eloy and Maricopa-Stanfield subbasins during the period of 1989 through 1996, with measured subsidence ranging from 0.032 ft to 0.22 ft (Evan and Pool, 2000).

Water released from the dewatering of aquitards likely attributed to part of the water level recovery observed in the study area. One of the detrimental effects of aquifer compaction is the permanent reduction of aquifer storage capacity. Once fine-grained materials have been dewatered and compacted, it is very difficult for water to be replaced. This nearly irreversible loss of storage capacity has a significant impact on future development of groundwater resources. The amount of water that can be stored in the aquifer after land subsidence is substantially less than could be stored before aquifer compaction occurred. Water levels in a subsided area respond to reduced water withdrawals in an exaggerated way due to the permanently reduced aquifer storage capacity, giving the appearance of more water in storage than may actually exist. It is very important to recognize these new characteristics of the aquifer system, particularly when trying to relate water level rises to increased aquifer storage.

7.0 Summary

B&N applied a three-step approach to review the Pinal AMA groundwater budget. First, the list of water budget components was checked for completeness. Then the groundwater budget was reproduced following ADWR's stated assumptions, so that any inconsistencies between the declared assumptions and the methods applied in the calculations could be detected. Finally, the assumptions and methods for each inflow and outflow component were evaluated in terms of validity and accuracy. During this assessment, extensive research was conducted through various channels, including publication research and communications with agencies and peers in the hydrology field, to investigate the availability and applicability of new methods on estimating these water budget components.

In general, ADWR's conceptual water budget is detailed and thorough, includes all the applicable inflow and outflow components. The stated assumptions are consistent with those actually applied in the budget estimation. Most water budget components are well estimated, although ADWR frequently was required to rely on data provided by other sources. B&N recommended significant modifications for only two of the budget components: agricultural irrigation recharge, and evapotranspiration. B&N suggested modifications or further investigation for four other budget components.

B&N suggests that the Mountain Front Recharge component may be overestimated. Several other components, Effluent Recharge, Major Drainage Recharge, Artificial Lake Recharge (Picacho Reservoir recharge), and Agricultural Irrigation Recharge, may be underestimated. Agricultural Irrigation Recharge is a dominant component, and influences the water budget far more than the other components. Except for Agricultural Irrigation Recharge, all other recharge components, whether overestimated or underestimated, have slight impact on the overall budget.

B&N proposes that agricultural recharge lag time is applicable to the Pinal AMA water budget. In the study area, the average depth to the water table is about 250 feet, and fine-grained silt, clay and evaporates form spatially extensive aquitards of great thickness. These are elements that contribute to agricultural recharge lag time. B&N's current estimate of lag time is approximated to be as long as 20 years, on average. A more reasonable estimate of agricultural recharge lag time can only be obtained through Pinal AMA groundwater flow model calibration supported by field data. The application of lag time yields significantly increased agricultural recharge to the water budget during the budget period. For example, the average annual agricultural recharge may increase to 102,000 AFY. This increased value for the agricultural recharge component is an observable phenomenon, the inclusion of which minimizes the discrepancies between ADWR's estimated water budget and the water level trends observed in the Pinal AMA. It is important to recognize that the use of a lag time does not create additional groundwater for the aquifer system. Instead, the incorporation of a lag time simply allows for the delay of previously recharged water and accounts for that water in the groundwater budget.

The primary evapotranspiration component was estimated by ADWR based on diverted Gila River water lost from storage in the Picacho Reservoir. This loss was not considered to be applicable as a groundwater budget component, since this component is a loss of surface water. For that reason, B&N suggests that this component be excluded from the groundwater budget.

With the revisions recommended by B&N for these inflow and outflow components, the aquifer change in storage (annual and cumulative) change dramatically. Though B&N's approximations will require refining by ADWR, the plotted trend for the change in storage is in favorable agreement with observed water level trends. The good agreement between these plotted data supports the conclusions made by B&N, and indicates that the recommended modifications would help to minimize the discrepancy that currently exists between ADWR's water budget and the water level trends observed in the Pinal AMA.

It is also important to point out that land subsidence in the study area has had substantial impact on the water budget. The residual aquifer compaction resulting from the historical aquifer overdraft and the presence of thick aquitards contribute to permanent reduction in aquifer storage capacity and, to a degree, apparent water level recovery. Water levels respond to decreased withdrawals in an exaggerated way, due to the permanently reduced aquifer storage capacity in compacted aquifer. Directly relating the magnitude of water level recovery to increased net aquifer recharge will overestimate aquifer storage.

8.0 Acknowledgements

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9.0 References

Anderson T.W., G.W. Freethy, and P. Tucgi, *Geohydrology and Water Resources of Alluvial Basins In South-Central Arizona and Parts of Adjacent States*, USGS professional Paper 1406–B, 1992.

Corkhill, E. F., M. Wickham, *Pinal Active Management Area Regional Groundwater Flow Model, Phase One: Hydrogeologic Framework, Water Budget and Phase One Recommendations, ADWR Modeling Report No.1*, Arizona Department of Water Resources, 1989.

Evans D.W., D.R. Pool, *Aquifer compaction and Groundwater Levels in South-Central Arizona*, USGS Water-Resources Investigations Report 99-4249, 2000.

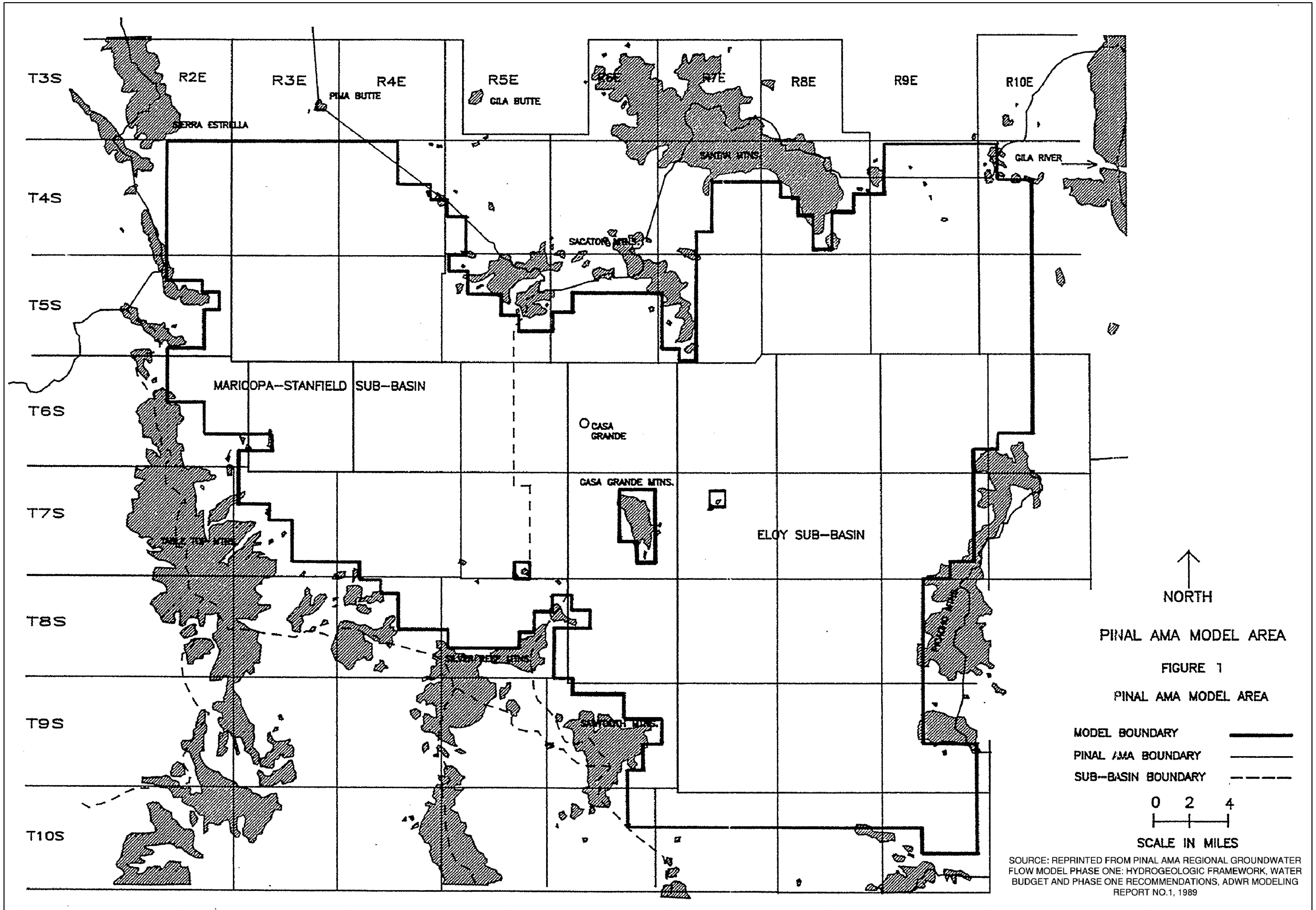
Goodrich , D.C. , D.G. Williams, C.L. Unkrich, J.F. Hogan, R.L. Scott, K.R. Hultine, D. Pool, A.L. Coes, and S. Miller, *Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona*, Groundwater Recharge in a Desert Environment: The Southwestern United States, Water Science and Applications Series, vol. 9, American Geophysical Union, Washington, D.C., 77-99, 2004,

Konieczki A.D., S.R. Anderson, *Evaluation of Groundwater Recharge Along the Gila River As a Result of the Flood of October 1983, In and Near the Gila River Indian Reservation, Maricopa and Pinal Counties, Arizona*, USGS Water-Resources Investigations Report 89-4148, 1990.

Laney, R.L., Raymond, R.H., and Winikka, C.C., *Maps showing Water-level Declines, Land Subsidence, and Earth Fissures in South-Central Arizona*, USGS Water-Resources Investigation Report 78-83, 1978.

Leighton D.A., Steven P. Phillips, *Simulation of Ground-water Flow and Land Subsidence in Antelope Valley Ground-water Basin, California*, USGS Water-Resources Investigation Report 03-4016, 2003.

Pool D., Carruth R., and Meehan W., *Hydrogeology of Picacho Basin, South-Central Arizona*, USGS Water-Resources Investigations Report 00-4277, 2001.



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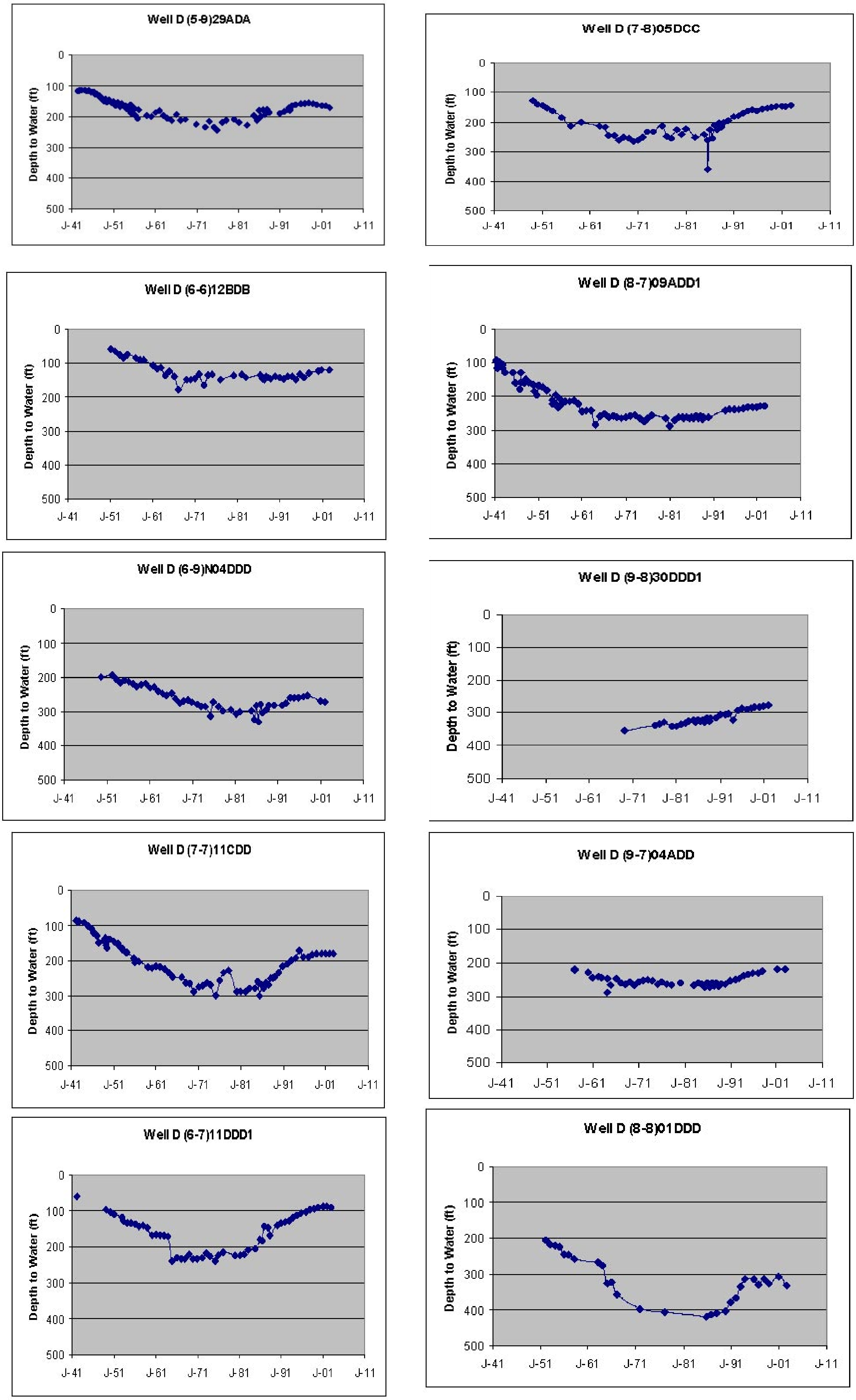
PINAL AMA MODEL AREA

FIGURE
1



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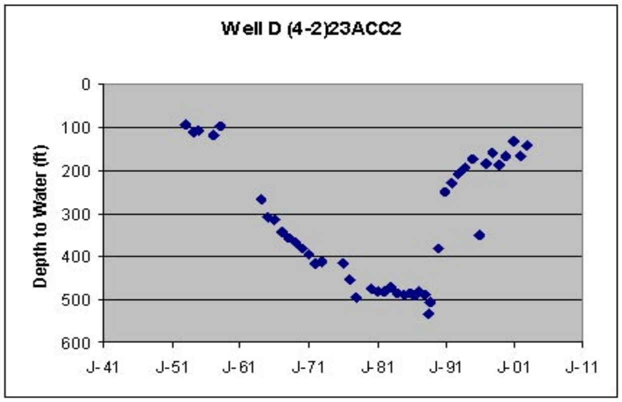
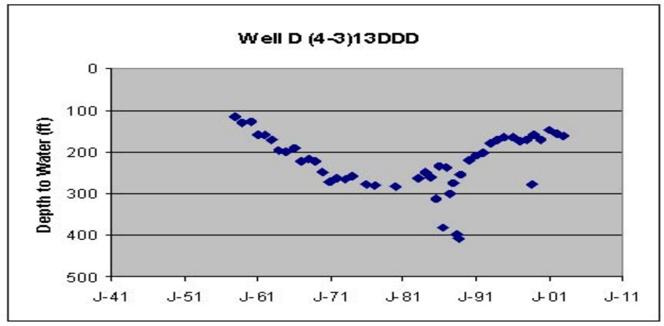
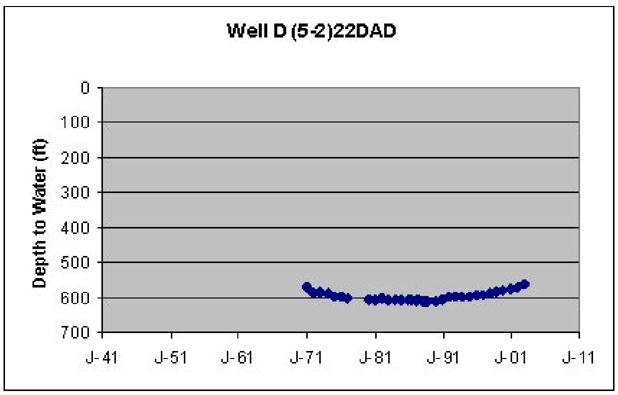
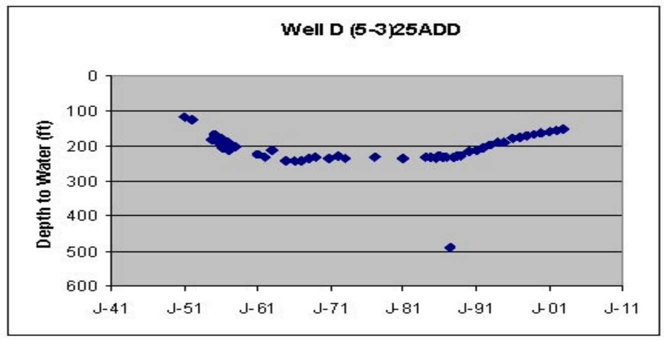
Hydrographs for Wells in Eloy Basin

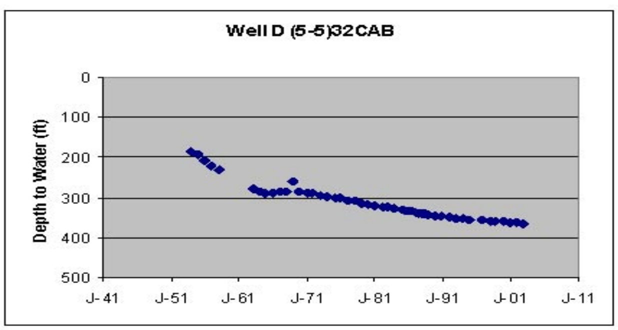
Figure 2

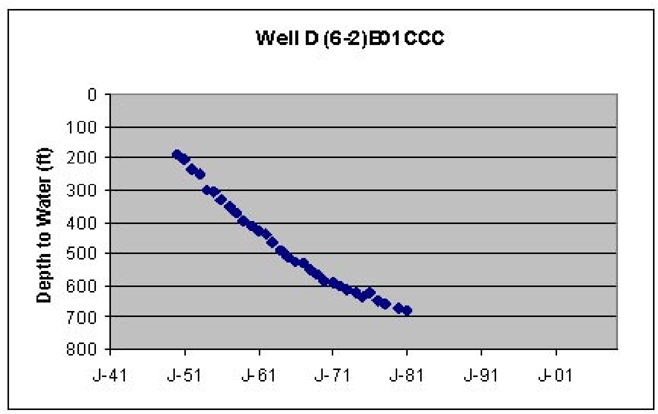


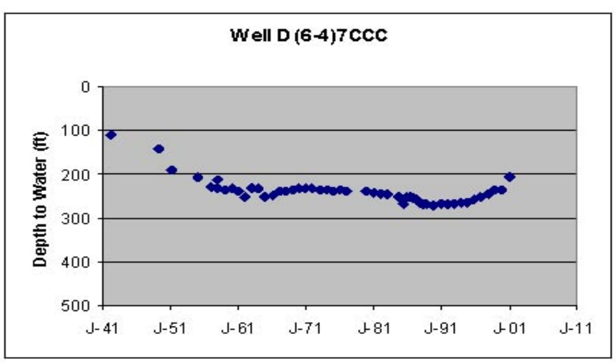


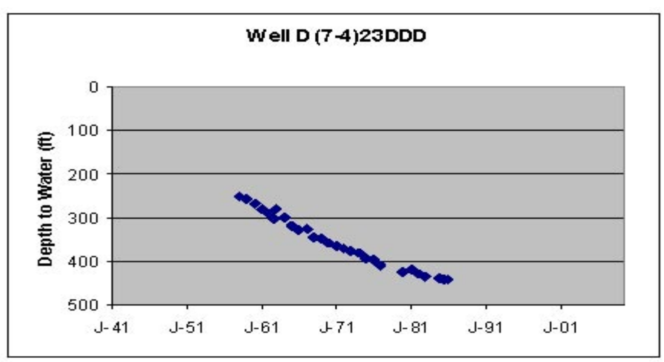












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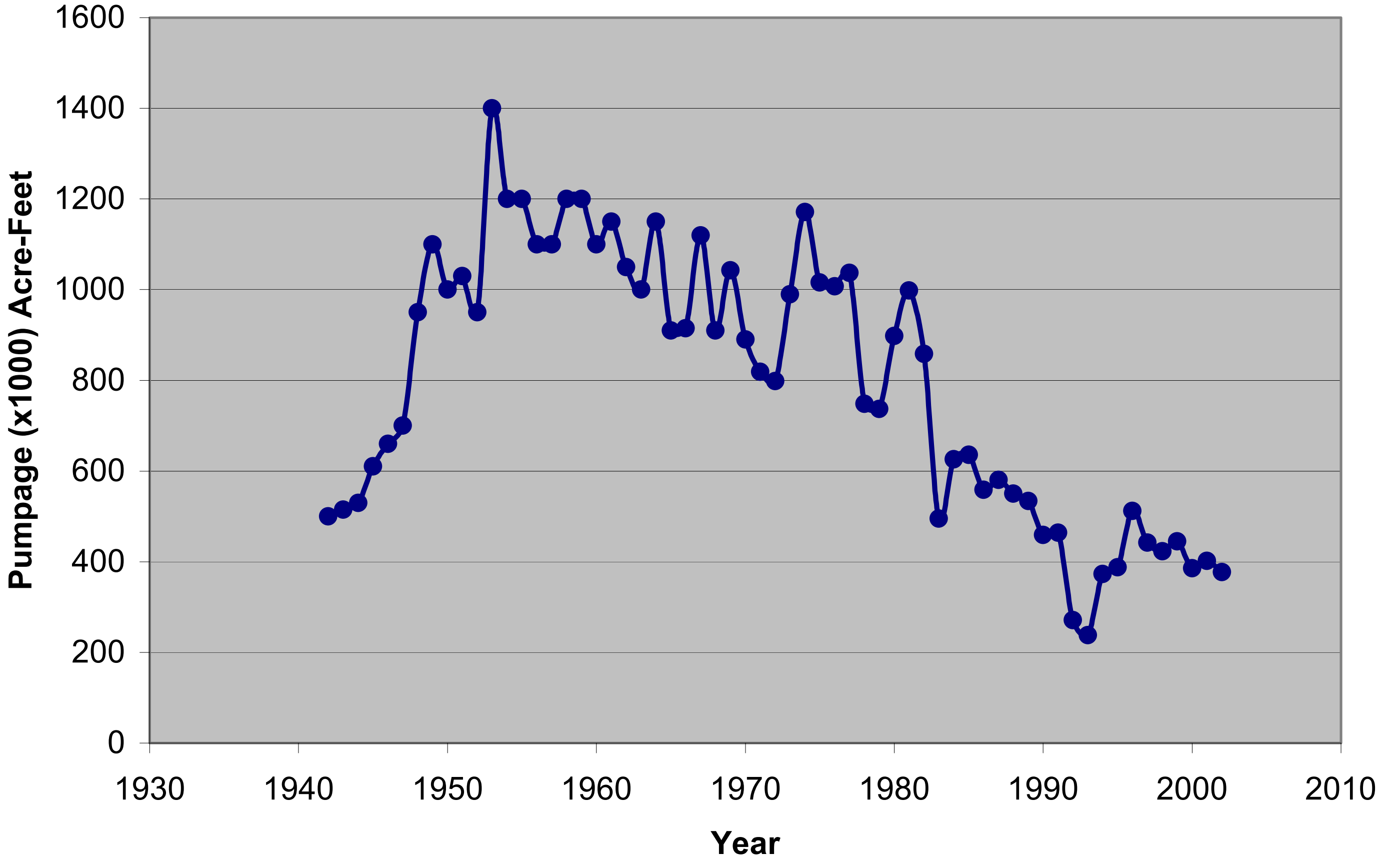
Hydrographs For Wells in Maricopa-Stanfield Basin

Figure 3



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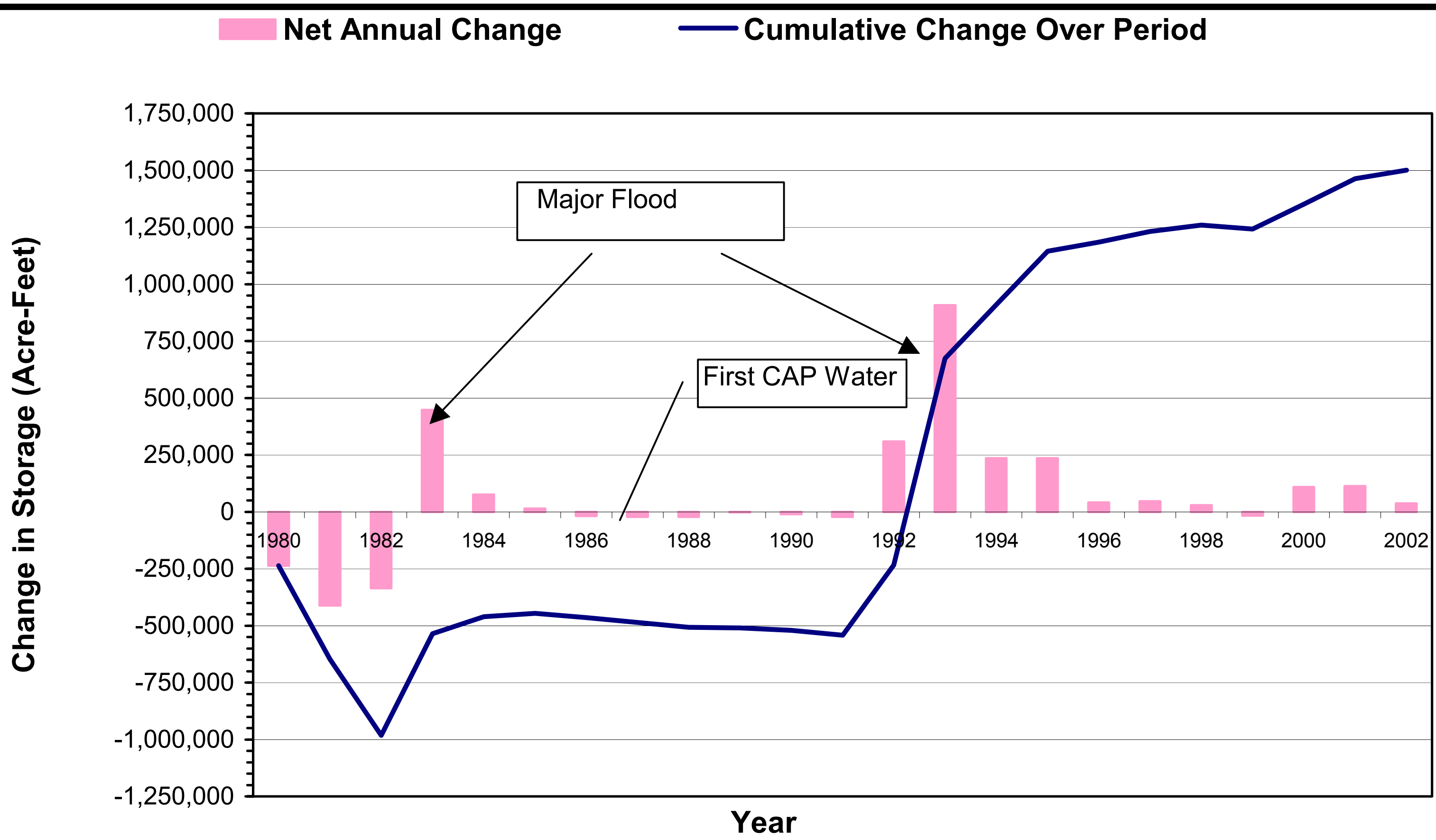
Historical Groundwater Pumpage in Pinal AMA

Figure 4



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Change in Aquifer Storage
Pinal AMA, 1980-2002

Figure 5